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14. ABSTRACT

Two numerical models focused on different scales are revised and extended to model surf zone hydrodynamics and sand transport driven by random waves in order to test with data measured during CROSSTEX and other field experiments. The two-phase model is successfully revised to be driven by measured time series of wave-current velocities and breaking wave turbulence during CROSSTEX experiment. When breaking wave turbulence is incorporated, the model is able to predict the strong suspension event observed during CROSSTEX. The new model will be used to study and evaluate the effect of breaking wave turbulence on sediment transport fluxes. A 2nd-order implicit scheme is implemented into the 2D RANS wave model (COBRAS). The new model is more numerically stable and accurate. We find that with a more accurate scheme, the predicted breaking wave turbulence kinetic energy is generally 30 to 100% smaller than the original 1st-order explicit scheme. Hence, this new scheme will improve our future plan to use COBRAS to study surf zone sediment transport.

15. SUBJECT TERMS

sediment transport, sheet flow, nearshore processes, breaking wave turbulence, two-phase flow

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CROSSTEX – Wave breaking, boundary layer processes, the resulting sediment transport and beach profile evolution

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LONG-TERM GOALS

To develop and test with laboratory and field data a robust modeling framework that predicts hydrodynamics and the fate of terrestrial and marine sediment in the heterogeneous environment.

OBJECTIVES

- Develop phase/depth-resolving numerical models for surf zone hydrodynamics and bottom sediment transport. Validate these models using data measured in CROSSTEX and other field experiments.
- Develop simplified phase-resolving formulations for concentrated sediment transport, suspended load transport and its near-bed boundary conditions under breaking waves.
- Calibrate the simplified formulations for predicting local sediment transport rate and beach profile evolution under breaking waves using measured data.

APPROACH

Two numerical models focus on different scales are revised and extended to model surf zone hydrodynamics and sand transport driven by random waves in order to test with data measured during CROSSTEX and other field experiments.

Boundary layer scale: A two-phase flow model (Hsu et al 2004) is extended to model sand transport driven by measured random wave-current forcing. In the physical experiment, measured near-bed time series of flow velocities are analyzed to extract (approximately) the time series of ensemble-averaged flow velocities and turbulence quantities (TKE and dissipation rate). These time series are then used to drive the two-phase model and to calculate and resulting sand transport from immobile sand bed to the dilute region of about 10cm above the bed. Physical experiments also provide measured suspended sand concentration in the intermediate to dilute region (volume concentration ~<15%), which can be used to validate the model. On the other hand, two-phase model results for concentrated sediment dynamics can bridge the missing information at the regime of concentration from about 15% to random-close packing (~63%), which is difficult to measure in the physical experiment.

Cross-shore scale: A two-dimensional phase/depth-resolving wave hydrodynamic model (COBRAS) solving Reynolds-Averaged Navier-Stokes equation (RANS with nonlinear eddy viscosity k-ε closure) for fluid flow and volume of fluid (VOF) method for free-surface tracking (Lin & Liu 1998; Hsu et al 2002) is modified to simulate field scale wave shoaling and breaking processes in the surf zone. A module for suspended load transport, reduced from the complete two-phase formulation (Hsu & Liu, 2004; Hsu et al. 2006) is coupled with COBRAS to calculate non-local sand transport.

Detailed model results along with the measured data will be analyzed to study the hydrodynamic and sediment transport processes in the surf zone and to develop simplified formulation for sediment transport rate and near-bed boundary conditions (e.g., reference concentration) used by suspended load model under the breaking waves.

WORK COMPLETED

Earlier this year, the Oregon State University team of the CROSSTEX project (Drs. Dan Cox, Tim Maddux and graduate student Chris Scott), who conducted the physical experiments on sand suspension under breaking wave on the summer of 2005, provided us with detailed data for measured sediment concentration and flow velocities in the surf zone along with a comprehensive data collection report (Scott 2006). For year 2006, most of our research efforts were devoted to numerical model developments and preliminary model-data comparison with CROSSTEX.

Two-phase model: Previously, an explicit first-order time integrator was adopted to calculate the coupled fluid phase and sediment phase equations (However, the sediment phase itself is calculated implicitly by a predictor-corrector scheme). Such explicit time-integrator for a two-phase system is conceptually faster than higher-order schemes. However, when driving the model with arbitrary shapes of random waves, the numerical scheme become less stable. In order to enhance the numerical stability when driven by random wave forcing, the numerical model is upgraded to a second-order implicit scheme. The resulting numerical model is much stable and allows using larger time-step size. Hence, the overall CPU time is similar to the first-order scheme. The new model is further used to study data measured during SISTEX99 (Dohmen-Janssen & Hanes 2005, not shown here) and during CROSSTEX (next section).

Surf zone wave model (COBRAS): Despite this 2D numerical code has been widely used for various applications (Lin & Liu 1998; Hsu et al 2002; Losada et al. 2005), most of the computations are limited to small laboratory scale (offshore water depth smaller than 1 meter) or short time simulation (~ 1 minute). In order to model proto-type scale random wave condition, the original code is revised. Last year, we adopted COBRAS to simulate SwashX field experiments (Raubenheimer 2002) that has a surf zone length of about 200m. We find that the numerical scheme is often unstable when calculating the larger waves in a wave group and the offshore boundary condition often failed (errors propagate back into the computational domain) after few hundred seconds of simulation. It is believe that this is caused by the low-order time integrator (1^{st}-order) adopted. This year the time-integrator of this numerical model is upgraded to a 2^{nd}-order implicit scheme and is shown to be more numerically stable and accurate when compared with field data measured during SwashX (next section).

RESULTS

Boundary layer scale

CROSSTEX data measured by Cox et al. consists of measurement of three-component flow velocities and concentration at several levels above the bed under breaking waves.

The sampling frequency of velocities is 50 Hz and hence the velocity time series consist of both wave-current velocities and high frequency turbulent fluctuations. With careful analysis, one can obtain approximately the concurrent time-series of wave velocity and turbulence at given level above the bed (Shaw & Trowbridge 2001; Scott et al. 2005).

Conventionally, measured velocity time series are used to drive the boundary-layer-based model to study the near bed boundary layer and sediment transport processes. However, this approach is based on the assumption that the free-surface generated turbulence does not reach the bottom boundary layer. In the present study, the breaking wave turbulence often penetrates into the water column and affects the near bed sediment transport (Cox et al. 2006). In order to exam the response of sediment under breaking wave, we use both the measured wave velocity and turbulent kinetic energy (TKE) time series (which records the breaking wave turbulence) at about 10cm above the bed to concurrently drive the two-phase model. We plan to try different ways to incorporate the measure surface-generated turbulence into the two-phase model. At this point, measure TKE time-series is specified as the top boundary condition for the k-equation (as opposed to on-flux boundary condition) while no-flux boundary condition remains unchanged for the turbulent dissipation rate. This method essentially uses measured TKE at the top of the wave boundary layer (~10cm) to force the turbulent field in the computational domain to mimic the effect of surface-generated turbulence on bottom boundary layer.

Fig 1 demonstrates the two-phase model results when using this new method as driver. Measured cross-shore wave velocity (Fig 1, solid-blue curve in the top panel) and TKE (solid-black curve) at 9cm above the bed are adopted to drive the two-phase model. The lower three panels show the model results for velocity (from left to right), turbulence intensity and sand concentration profiles at three instants during the passage of broken waves. When measured TKE is used as additional driver to the two-phase model (black curves), calculated turbulence is large within the entire boundary layer when the breaking wave turbulence at 9cm above the bed is large (instants (t2) and (t3)). On the other hand, using the conventional method (on-flux top boundary condition for TKE), the TKE is much smaller in the boundary layer (red-dashed curves). More importantly, it is only when the breaking wave turbulence is considered that the modeled concentration profiles are consistent with measured ones (compare solid curves with symbols). When the breaking wave turbulence is small (see (t1)), modeled concentrations are similar regardless of whether the measured TKE is used to drive the model and calculated concentration profiles decrease rapidly away from the bed, consistent with measured data. On the other hand, when breaking wave turbulence is strong ((t2) and (t3)), measured data suggests that the concentration is much larger in the boundary layer and is of more uniform distribution (see (t3)), representing strong burst of sand suspension due to breaking wave turbulence. This feature is captured by the two-phase model only when measured TKE is used as an additional forcing apply as top boundary condition (at (t3), the red-dashed curve represent much smaller concentration in the boundary layer than the measured data and that represented by the black-solid curve). The preliminary results shown here are encouraging because they suggest that one can use a boundary-layer-based sediment transport model to exam the effect of breaking wave turbulence provided that measured turbulence above the boundary layer is used as top boundary condition.

However, we believe at this point the most critical uncertainty in this approach is an appropriate method to truthfully extract turbulence. By slightly varying the cut-off frequency, one obtains changes in TKE by a factor of 2. In the upcoming year, we will continue our analysis and model-data comparison. Trowbridge is currently testing a robust method to extract turbulent energy dissipations from the measured velocity time series so that both TKE and its dissipation rate are used as top boundary conditions of the model. Later this year, we will use more rigorous separation technique developed by Shaw and Trowbridge (2001) to extract the turbulence from the random wave field.

Cross-shore scale

The Swashx field data (Raubenheimer 2002) for wave hydrodynamics within the surf zone is utilized to test the capability of COBRAS for large-scale surf zone hydrodynamic computation (Swashx data is obtained in collaboration with Dr. Britt Raubenheimer). According to the lesson learned from year 1, we find that existing COBRAS with 1^{st}-order explicit time-integrator is often unstable under energetic random wave forcing. This significantly limits the capability of COBRAS for future extension on surf zone sediment transport in which random waves and long time computation (>O(100) waves) are necessary. Hence, in the beginning of year 2, we have developed a 2^{nd}-order implicit scheme in conjunction with the existing two-step projection method (e.g., Bell et al. 1989). The new numerical scheme is computationally stable and can receive arbitrary random wave input. Compared with the 1^{st}-order scheme, the new 2^{nd}-order scheme is certainly more accurate in term of the truncation errors. More importantly, the new scheme gives lower numerical diffusion and hence smaller turbulence in the numerical solution (such as turbulence kinetic energy) when compared with lower order scheme.

Fig. 2 presents the model-data comparisons with Swashx for a 5-minute event. Measured offshore wave height at x=185.5m is used to drive the numerical model. The numerical model with 2^{nd}-order scheme reproduces well the wave setup (red), r.m.s. wave height (black) in the surf zone (Fig 2, top panel). The predicted (black-solid curve) and measured (red-dashed curve) time-dependent free surface elevation at *x=86m* (second panel) also match well. More importantly, the new model predicts the undertow profiles (black-dotted curves in the third panel of Fig 2) at several different locations in the surf and inner-surf zones that compare fairly well with the measured data (red symbol). On the other hand, using the 1^{st}-order scheme (blue-dashed curve) the undertow profiles are often over-predicted (by about 50-100%) because of the over-prediction on turbulent kinetic energy (fourth panels in Fig 2).

Notice that the over-prediction on undertow and TKE in the 1^{st}-order scheme may have great implication to the subsequent prediction on sediment transport processes. Clearly, utilizing a higher accuracy scheme is crucial for the present studies. Currently, we collaborate with Dr. Cox and Dr. Sungwon Shin at Oregon State University to conduct more complete evaluations on the 2^{nd}-order scheme for predicting wave skewness, undertow and TKE using detailed data measured during CROSSTEX pilot experiments (Scott et al. 2005).

IMPACT/APPLICATIONS

The present research efforts focus on developing and validating detailed numerical models for sediment transport and wave hydrodynamics. This year we specifically focus on refining the numerical schemes in the two-phase model and RANS wave model so that they will be more robust and user-friendly in the future. It expected that by the end of this 4-year project, these numerical tools will be made available to the research community.

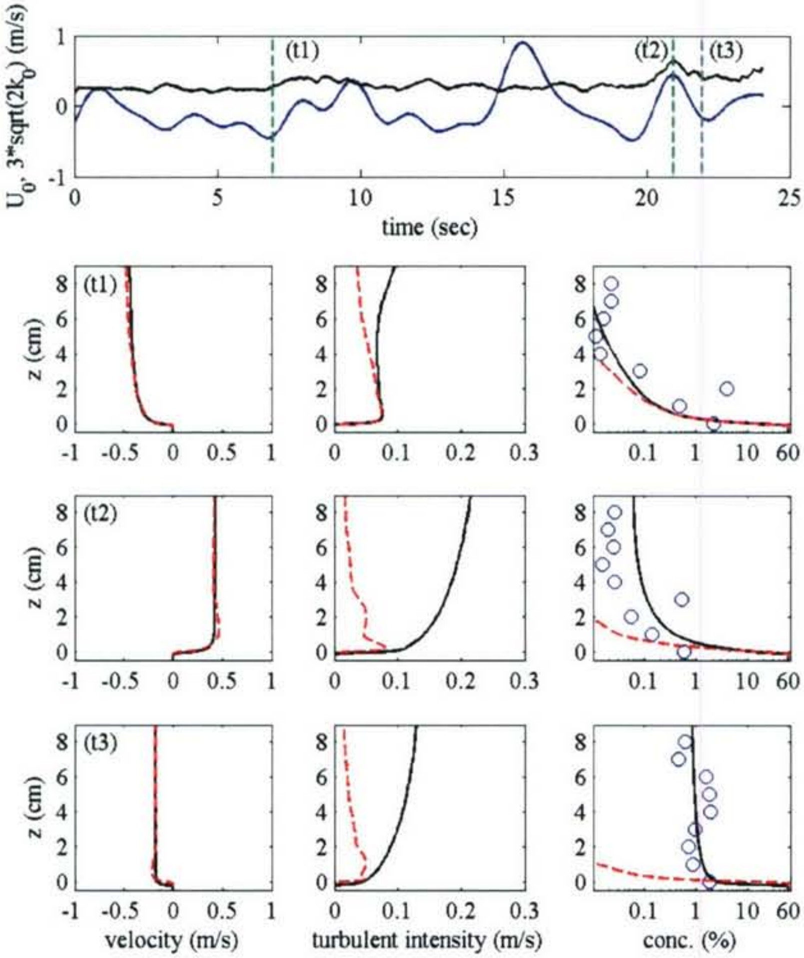

Fig. 1: Measured wave velocity (top panel, blue curve) and TKE (black curve) at 9cm above the bed are used to drive the two-phase model. The model predicts flow velocity, turbulent intensity and sediment concentration (left to right) at three instants (t1)-(t3) during the passage of the breaking wave. When breaking wave turbulence is strong (e.g., (t2) and (t3)), both measured data (symbols) and predicted concentration (solid-black curve) suggest a strong sediment suspension event (see (t3)). However, model results without using the measured TKE as forcing failed to predict the suspension event (red-dashed curve at (t3)).

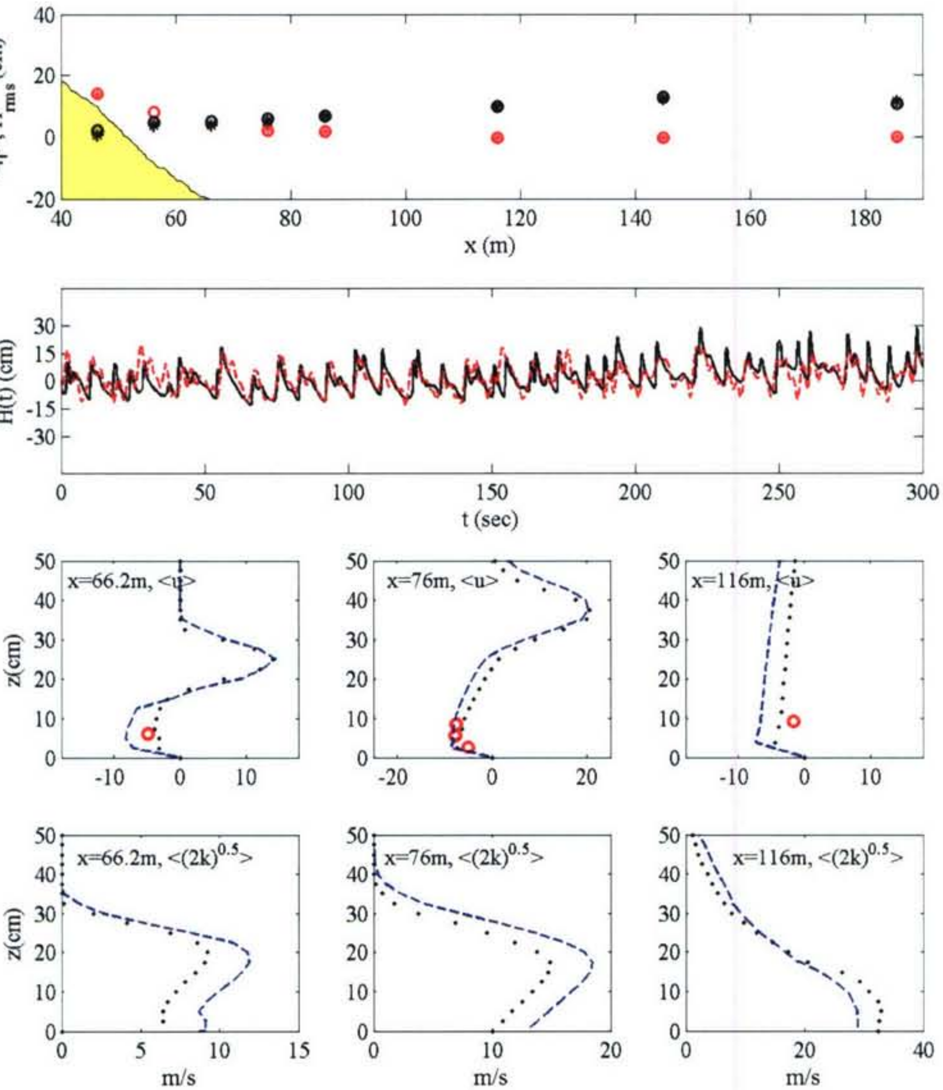

Fig. 2: Model-data comparisons on surf zone hydrodynamic for an event (Oct 9th, 1600hr) measured during Swashx. Top panel: measured (circles) and predicted (crosses) wave setup (red) and r.m.s. wave height (black). Second panel, time-dependent free-surface elevation at *x=86m* for the predicted (solid-black) and measured (dashed-red) results. Third panel: time-averaged (100sec) currents (undertows) at three locations (left to right) in the surf zone with red-circles represent measured data, black-dots represent predict results with 2nd-order implicit scheme and bule-dashed curve represent 1st-order explicit scheme. Due to over-prediction of flow turbulence (see time-averaged turbulence intensity in the 4th panel) in the surf zone using the 1st-oder scheme, it also over-predicts the undertows.

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